# Insight into the Contact Impedance between the Electrode and the Skin Surface for Electrophysical Recordings

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**ABSTRACT:** To obtain a performance improved dry electrode for bioelectrical activity detection is still a challenge, which is mainly due to the poor fundamental understanding on the impedance of the electrode−skin interface. Herein, the impedance between the electrode and the skin interface of three types of electrodes, which are the wet electrode, semidry electrode, and dry electrode, is investigated with electrochemical impedance spectroscopy combined with the spectra fitting technique. The parameters of performance duration, potential, and frequency associated with the impedance are explored for these three types of electrodes. The overall impedance is roughly constant within the performance duration and the potential applied in this study. Along with the frequency decreases, the impedance of the dry electrode reduces faster and is more complicated compared with the other two types of electrodes. Moreover, the results computed with the equivalent circuits show that the charge transfer resistance is additionally present compared to the wet and semidry electrodes. This large and additional charge transfer resistance may explain its relatively poorer electrophysiological properties.
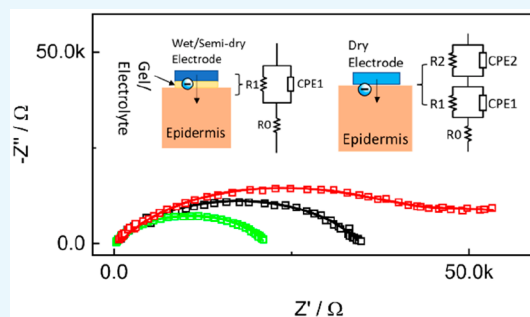
## 1. INTRODUCTION

The body electrical activity is generated by the concentration gradients and electrostatic gradients of ions within the cell, and it is based on the types of ion channels.[1] The charge concentration difference between the cell membrane creates electrical signals. They are considered as the language for the neuron communications between one another. Moreover, they also contain a lot of body information. Clinical doctors use this information for disease diagnosis.[2] Researchers in neurocognitive science use the obtained body electrical signals for the fundamental studies to understand the brain functions in different areas.[3] Engineers use body electrical signals in pursuit of precisely operating the robots or artificial limbs.[4] Many studies have extensively been carried out pursuing to acquire the body electrical signals, especially from the skin surface with a noninvasive electrode.

The electrode is the most crucial component for the surface electrical signal acquisition system, especially for EEG (electroencephalography), EMG (electromyography), and ECG (electrocardiograph).[5] There are three different types of noninvasive surface electrodes commercially available.[6,7] They are named the wet electrode, semidry electrode,[8] and dry electrode,[9] and their configurations are illustrated in Figure 1. The wet electrode consists of the Ag/AgCl piece and the gel. It is a traditional and widely used one in clinics and lab experiments, typically for the EEG. However, it is considerably time-consuming for the setup installation.[10] Recently, the semidry and dry electrodes have been developed to tackle

these drawbacks of the wet electrode. The semidry electrode is supposed to use a jellylike electrolyte that is relatively less humidity compared to the gel of the wet electrode.[11,12] This one is more often to be used in EMG and ECG due to its enhanced ease of use compared to the wet electrode in un/ installation. Another one is the dry electrode that does not need any gel or electrolyte between the electrode and the skin.[13] It is accepted as the most promising electrode for the electrophysiological signal acquisition in the community.[14] With the lack of the wet gel or jellylike electrolyte, it is much easier to use, and it also comforts the subjects or patients.

Recently, a novel ceramic-based semidry electrode was developed by Wang et al. for brain−computer interface applications.[15] Its electrophysiological performance was compared with the traditional wet electrode. The result shows that the semidry electrode is better than the wet electrode in comfort. But further optimization in the bioelectrical signal acquisition ability is still thought to be needed for more application scenarios. This group also developed another hydrogel-based semidry EEG electrode
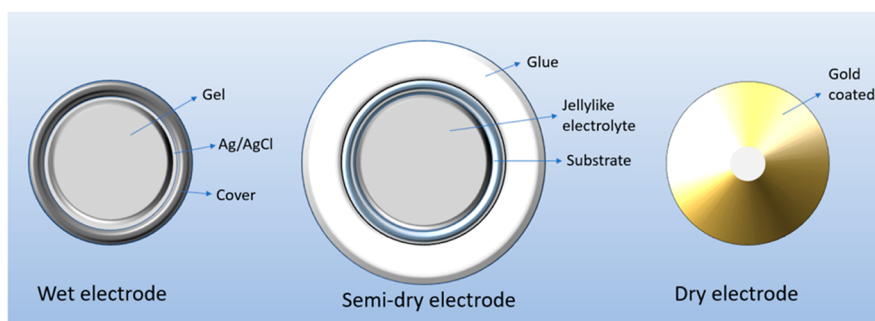
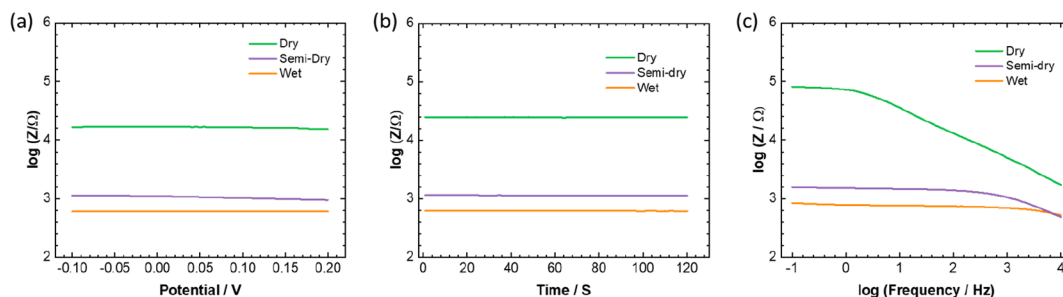**Figure 1.** Schematics of the wet electrode, semidry electrode, dry electrode.



**Figure 2.** Impedance of dry (green), semidry (purple), and wet (orange) electrodes obtained on the skin surface of a rat along with potential (a), performance duration (b), and frequency (c). The impedance changes along with performperformance duration and potential were recorded at 20 Hz.

that exhibited similar performance compared to the wet electrode.[11] Radüntz compared the signal quality of six different EEG devices, in which four are equipped with dry electrodes and two are equipped with wet electrodes.[16] The gel-based EEG system could not be surpassed by the gel-free system. Hinrichs and co-workers also compared the dry electrode EEG system to the wet electrode EEG system for clinical applications.[17] The artifacts of the dry electrode equipped system are higher than those of the wet electrode system. However, the dry electrode and semidry electrode are more preferred by the patients and the volunteers. It is widely accepted that the dry electrode is more feasible for the bioelectrical activity detection. But it is still challenging to achieve an improved electrophysiological signal acquisition ability of the dry electrode. This is mainly because the fundamental understanding of the interface between the electrode and the skin is still not clear.

Herein, we study the interfacial impedance between the electrode and the skin using electrochemical impedance spectra technology. The experiments were carried out on the skin surface of the rat and the arm of the human with a three-electrode system. Three types of popular electrodes (dry, semidry, and wet electrodes) acted as the working electrode. These three types of electrodes correspond to with electrolyte, with jellylike electrolyte, and without electrolyte, respectively. On the skin of the rat, the wet electrode presents the lowest impedance. Whereas, the impedance of the semi-dry electrode on the skin of the human arm is the lowest. The values obtained by the wet and semidry electrodes are very similar on both the skin surfaces of the rat and human arm. Interestingly, the impedance amplitude recorded by the dry electrode on the skin of the rat is much larger than those of the other two electrodes. However, the impedance amplitude deviation recorded on the skin surface of the human arm is very small among these three types of electrodes. The equivalent circuit

computational fitting study indicates that this difference originates from the charge transfer resistance of the interface between the electrodes and the skin. The charge transfer barrier on the skin of the rat is much larger than the surface of the arm of the human. Moreover, the charge transfer resistance of the dry electrode is the largest one, which provided an explanation to the reduced signal quality compared to the wet and the semidry electrodes.

## 2. EXPERIMENTAL SECTION

**Skin Preparation.** Before the impedance recording experiments, the skin preparation was carried out. The rat is alive, but ketamine was used to allow it to calm down in order to ease the electrode installation. The diameters of the dry, semidry, and wet electrodes are 10.0, 9.0, and 7.5 mm, respectively. The skin prepared for the experiment was around 30 cm$^2$, and around 70% was used for the impedance testing. The hair of the selected area of the rat was cut to 0.8 mm, and then the skin was cleaned with alcohol. The selected area on the arm for impedance recording was also cleaned with alcohol.

**Impedance.** The impedance recording experiments were carried out in the temperature- (25 °C) and humidity-(51%) controlled room with the Electrochemical station of CHI760E (CH Instruments Corp.) with three electrodes. Two wet electrodes acted as the counter electrode and reference electrode. The reference was placed between the counter and wet electrodes. The dry (Wuhan Greentek Pty. Ltd.), semidry (Wuhan Greentek Pty. Ltd.), and wet (Neuroscan EEG) electrodes were used as the working electrodes. The potential range was from −0.1 to 0.2 V at 20 Hz for the potential experiment. The influence of the performance duration was studied within 120 s at 20 Hz. The frequency was conducted between 0.1 and 10k Hz to investigate the impedance change
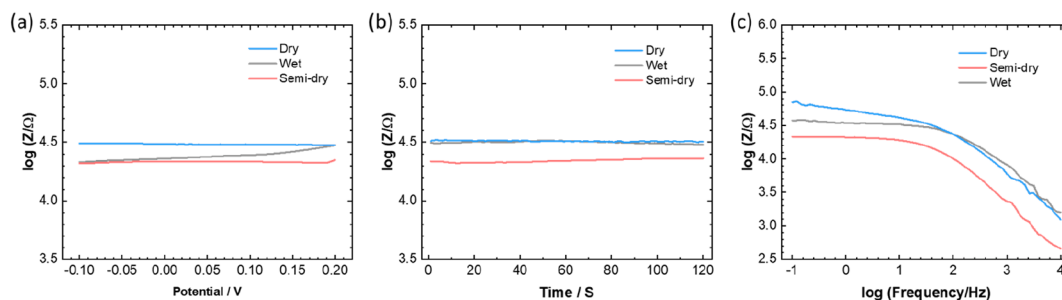
**Figure 3.** Impedance of dry (blue), semidry (black), and wet (red) electrodes on the arm surface of a human along with potential (a), time (b), and frequency (c). The impedance changes of time and potential were recorded at 20 Hz.

with frequency. The impedance fitting was carried out with the EIS Spectrum Analyzer (copyright: Aliaksandr Bandarenka and Genady Ragoisha).[18]

## 3. RESULTS

The impedance between the electrode and the skin usually strongly affects the acquired bioelectrical signal quality. The potential amplitude, performance duration, and signal frequency are considered the main factors that affect the impedance between the electrode and the skin. Therefore, we start the experiment with the rat to investigate relationships between the impedance and these three parameters, as shown in Figure 2. The open circuit voltages (OCVs) of the dry, semidry, and wet electrodes on the arm were 0.0151, 0.0191, and −0.0032 V, respectively. The OCVs on the skin of rat of the dry, semidry, and wet electrodes were −0.1218, −0.0196, and −0.1687 V, respectively. The potential amplitude within −0.1∼0.2 V does not affect the impedance (Figure 2a). But the impedance amplitude is affected by the electrode type. The dry electrode shows the highest impedance, which is more than 4 orders of magnitude. This is almost 50% larger than the value of the wet electrode in order. The impedance of the semidry electrode is between that of the dry electrode and the wet electrode, and it is just slightly higher than that of the wet electrode. Within the performance duration of 120 s, there is no change observed at all for all three different types of electrodes, as presented in Figure 2b. The same trend was shown in that the impedance value changes due to the type of the electrode. The dry electrode shows the largest impedance, and the wet electrode shows the smallest impedance. Figure 1c exhibits the impedance evolution along with the frequency from 0.1 to 10k Hz. The dry electrode also shows the largest impedance in amplitude, while the wet electrode is the smallest one (Figure 2c). Moreover, the impedance amplitude increases along with the decrease of frequency and then remains stable. The impedance amplitude deviation and the decrease speed from high to low frequency of the dry electrode is the largest one compared to the other two types of electrodes. The impedance of the dry electrode reaches to around 5 orders of magnitude at around 1 Hz, while the impedance of the semidry electrode reaches to around 3 orders of magnitude at 100 Hz and 2.8 orders of magnitude at 1000 Hz for the wet electrode.

The electrode−skin impedance was also performed on the skin surface of the arm of the human. The results are shown in Figure 3. While changing the potential from −0.1 to 0.2 V, the overall impedance values are lower than 4.0 in order of magnitude. Similarly, the impedance of the dry electrode is still the largest one, whereas the deviation between the dry electrode and the other two electrodes is less than 0.5 orders in

magnitude, as shown in Figure 3a. The semidry electrode shows the lowest impedance, and the wet electrode is moderate. Within 120 s (Figure 3b), the impedances of all three types of electrodes are stable, indicating a good stability within this performance duration. The impedance variety in frequency was investigated between 0.1 and 10k Hz. When the frequency is lower than 1.5 order in magnitude, their impedance is between 4 and 5 orders in magnitude. When it exceeds 100 Hz, the impedance of all electrodes decreases quickly, as shown in Figure 3c. The semidry electrode shows the smallest impedance between 0.1 and 100 Hz compared with the other two electrodes. The impedance of the dry electrode decreases with the increase of the frequency. The difference between low and high frequencies of the dry electrode is 1.8 orders, which is larger than that of the wet and semidry electrode of 1.6 and 1.7, respectively. As a result, the wet electrode shows the largest impedance in the range of high frequencies.

## 4. DISCUSSION

A large impedance difference can be clearly observed between the rat skin and the arm skin of the human. The impedance detected both by the wet and by the semidry electrode obtained from the skin surface of the rat is over one order higher than that obtained from the human arm. This is caused by the hair remained on the skin surface of rat. The hair might reduce the contact area between the electrolyte and the skin.[19] It is known that the impedance is inversely related to the contact area. The hair reduces the effective contact area between the electrode and the skin, leading to a larger contact impedance.[20] On the other hand, the semidry electrode shows the smallest impedance on the surface of the arm, which is probably due to the good fixation. The semidry electrode can easily be self-adhered on the surface of the arm, while the wet and dry electrodes were fixed by the normal tape. However, the semidry electrode shows larger impedance compared to the wet electrode on the skin surface of the rat. This is because the small size and the hair of the rat make it more difficult to be fixed. Besides, the mobility of the jellylike electrolyte is relatively poorer than that of the gel, which means the jellylike electrolyte are more difficult to through the hair of the rat compared to the gel electrolyte. This results in relatively larger impedance on the surface of the rat compared to the arm. The results indicate that impedance strongly depends on the hair and fixation circumstance. As a result, the gel-like electrode is more suitable for hairy subjects, while the dry and semidry ones are more suitable for the hairless subjects.

More importantly, the charge behavior on the electrode interface is also of importance to understand the impedance
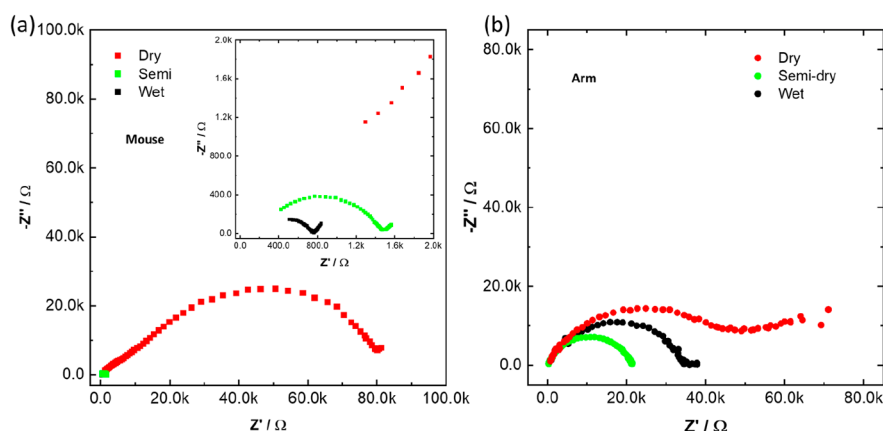
**Figure 4.** Nyquist plots of dry (red), semidry (green), and wet electrodes (black) acquired on the skin surface of the rat (a) and the arm of a human (b). The impedance was measured between 0.1 and 1k Hz.
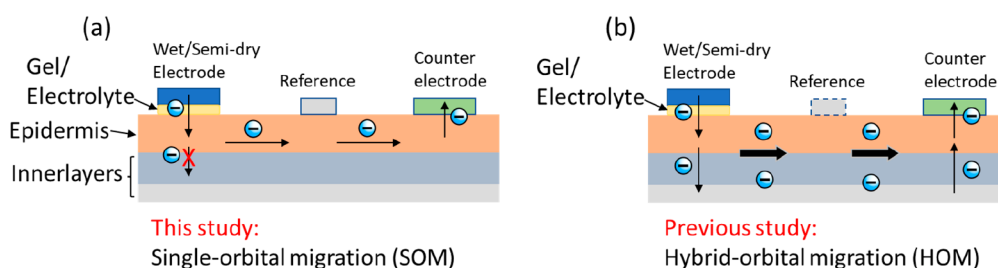


**Figure 5.** Comparison of charge migration over the electrode and skin interface between (a) this study and (b) the previous study.

behavior of different types of electrodes. Electrochemical impedance spectroscopy is a technique to analyze the interface electric behavior. Figure 4 shows the Nyquist plots of the dry, semidry, and wet electrodes detected on the skin surface of the rat and the arm of the human. The spectra obtained from the skin surface of the rat by the wet and the semidry electrode show a semicircle, as presented in Figure 4a. Due to the existence of hair, the Nyquist plot of the dry electrode is varied. At high frequency, there is a semicircle that is due to the reduced contact area. This leads to the increase of the electric resistance. On the other hand, the second semicircle at the medium frequency is caused by the capacitance that is composited by the electrode, hair, and skin. As a result, the overall impedance obtained by the wet electrode is less than 800 Ω, while it is around 1.5k Ω for the semidry electrode and 80k Ω for the dry electrode. Figure 4b shows the Nyquist plots obtained on the skin surface of the arm of the human with wet, semidry, and dry electrodes. It is clearly observed that the spectra shapes obtained by the wet and semidry electrodes are similar to the spectra shapes obtained on the skin surface of the rat. But the spectrum shape of the dry electrode obtained from the arm of the human is different from the spectrum obtained from the rat. This is mainly caused by the less hairy skin surface on the arm. The total impedance obtained on the arm is 20k Ω for the semidry electrode and 35k Ω for the wet electrode. Not surprisingly, the dry electrode still shows the largest value of around 50k Ω.

Before the discussion about the equivalent study, the charge migration over the electrode and skin interface should be elucidated. It is known that the electric current is generated by neurons/cells.[21] And the charge shall overcome the barriers of the skin and electrode and then migrate through the cable to the detector, as reported in most publications.[10,22] However,

the charge migration during the impedance analysis differs from the electrical activity generated from the brain. The current for the impedance analysis is very weak. It is impossible for the charge to pass through the epidermis to the inner layer. Besides, the inner layers also increase the overall resistance, prohibiting the charge migration through the inner layer. Figure 5 compares the charge migration over the electrode and skin interface between this and the previous study. However, many impedance discussions about the electrode−skin contact are based on the knowledge of the multilayers of skin, namely, hybrid−orbital migration (HOM).[7,23,24] To have better clarity, this study discusses impedance based on the electrode and the epidermic layer, namely, the single-orbital migration (SOM).

An equivalent circuit is frequently used to explain the interface electrical activity. There are already three different equivalent circuits proposed by Thomasset, Kirkup, and Lapicque, as shown in Figure 6. They are used to explore
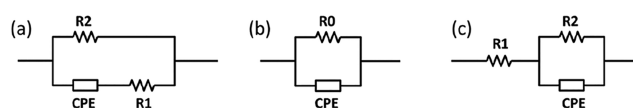


**Figure 6.** Equivalent circuits proposed by Thomasset[30] (a), Kirkup[25] (b), and Lapicque[26] (c). Reprinted with permission from ref 24. Copyright 2003 Elsevier.

the electrode−skin interface electrical activity. Interestingly, the difference among them is the position of the R1 resistor with different cutoff frequencies, although they are all evaluated with the wet Ag/AgCl electrode. Fricke explained that the R1 is an intracellular resistance,[28,29] which was also proved by Zhang and co-workers.[27] The Kirkup model is also adopted to study the electrode−skin impedance between 1 and

950 Hz. Hewson et al.[24] studied the impedance obtained between 1 and 16 348 Hz by using the Lapicque model with the pregelled Ag/AgCl electrode. Based on the previous reports and the cutoff frequency used in our study, the model shown in Figure 6a is used to explore the electrical activity of the interface generated by the wet electrode and skin as well as the semidry electrode and skin. The analysis is carried out between 1 and 10k Hz. Since the rat hair strongly affects the impedance results, only the impedance data obtained from the arm are analyzed.

Nyquist plots obtained with the wet and semidry electrodes are analyzed with the model of Figure 7a. The results are listed
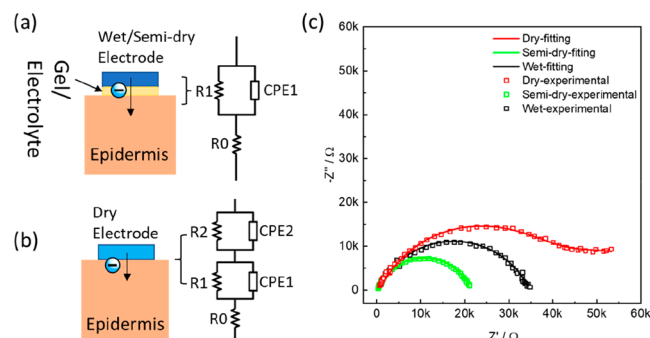


**Figure 7.** Equivalent circuits applied to fit the results obtained by the (a) wet and semidry electrodes as well as the (b) dry electrode. (c) Fitting results of the impedance spectra obtained on the skin surface of the arm with wet (black), semidry (green), and dry (red) electrodes. Dots and lines indicate the experimental and fitting results, respectively.

**Table 1. Fitting Results of the Impedance Obtained by Wet, Semidry, and Dry Electrodes**

|         | R0 (Ω) | R1 (Ω) | CPE1 (F)              | R2 (Ω) | CPE2 (F)              |
|---------|--------|--------|----------------------|--------|----------------------|
| wet     | 271    | 34464  | $1.9428 \times 10^{-7}$ | -      | -                    |
| semidry | 248    | 21905  | $4.6994 \times 10^{-7}$ | -      | -                    |
| dry     | 692    | 40359  | $2.6925 \times 10^{-7}$ | 27632  | $1.2716 \times 10^{-5}$ |

in Table 1. The values of intercellular resistances are very low for both, indicating that the intercellular resistance is neglectable in the range of frequencies used in this report. This is consistent with the result reported by Hewson.[24] R1 in the model of Figure 7a represents the resistance of the system. The value deviation of R1 between wet and semidry electrodes is very small, which indicates that the conductivity difference between the gel and the jellylike electrolyte is low. Whereas, the R2 represents the resistance of the electrode−skin interface. This resistance of the semidry electrode is smaller than that of the wet electrode. This is supposed to result from the positive effect of glue, which ensures a stable and good contact between the skin and the electrode. The equivalent circuit used for analyzing the dry electrode data is different from that of other electrodes, as shown in Figure 7b. The R0 and R1 here also represent the same system and the electrode−skin interface resistances. These are the same as those of the wet and semidry electrode. Meanwhile, the R2 indicates the charge transfer resistance due to the lack of conductive electrolyte (Figure 7c). It is not surprising that the

dry electrode shows a much larger R1 and R2 than the wet and semidry electrodes. This might explain the electroencephalographic property drop of the dry electrode compared with the other two types of electrodes.

## 5. CONCLUSION

The impedances between the skin and the three different types of frequently used electrodes were investigated using the electrochemical impedance spectra technique. These three types of electrodes are wet, semidry, and dry electrodes. The impedance evolution along the performance duration, potential, and frequency were explored using the electrochemical impedance analyzer. Within the performance duration of 120 s and the potential range between −0.1 and 0.2 V, the impedance of all electrodes is stable on both the skin surfaces of the rat and arm of the human. But the impedance change of the dry electrode is much larger than those of the other two electrodes. The impedance deviation between different types of electrodes obtained on the skin surface of the rat is much larger than that recorded on the skin surface of the arm of the human. This is related to the hairier condition on the skin of rat than the human arm. Furthermore, the equivalent circuits of impedance spectra of the dry electrode were studied to clarify its relatively poor electrophysiological performance using the equivalent circuits. The computational results show that the interfacial resistance is larger than those of the other two types of electrodes. Moreover, an extra resistance from the charge transfer is also present. Its amplitude is even larger than the interfacial resistance. This explains the reduced electrophysiological properties of the dry electrode.

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**Notes**

The authors declare no competing financial interest.

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